THE ACOUSTIC FIELD OF MARINE SEISMIC AIRGUNS AND THEIR POTENTIAL IMPACT ON MARINE ANIMALS

Les Hatton CISM, Kingston University, London

1 INTRODUCTION

Marine seismic airguns have been a phenomenally successful exploration source in seismology. Prior to their introduction, dynamite and various other sources were used to inject acoustic energy into the earth both for exploration seismology and also for earthquake studies. The advent of the airgun in the 1970s very quickly drove out almost all the other sources. Airguns proved to be reliable, consistent and as they evacuated compressed air, they were considered an environmentally clean source, [1].

Airguns are produced by a small number of manufacturers and although there are some structural differences affecting reliability and consistency of the output pulse, they are broadly very similar. In deference to their common use in the exploration industry, that industry's rather casual use of units will be adopted in which airgun pressure is specified in pounds per square inch (psi), bars *and* bar-m, volume in cu.in. rather than litres and distances strangely in m. Measurements of the acoustic field vary even more but they will be described as they arise.

Airguns come in a range of volumes typically 10-2000 cu.in. (0.16 – 32.77 litres) and in both exploration seismology and earthquake seismology are operated nominally in the range 1800-2500 psi pressure (124-173 bars) with the value 2000psi (138 bars) being by far the most commonly used. They are almost invariably operated in arrays of 4-48 guns with a typical array being around 4000 cu.in (about 65 litres) made up of around 30 guns of various sizes. Multi-gun arrays are used for several reasons:-

1. To provide more acoustic energy in order to penetrate sufficiently far in the earth to illuminate the features of interest, (down to about 8km in exploration seismology and as deep as possible for earthquake seismology, typically 30km). The peak pressure output of an airgun is only proportional to the cube root of the volume approximately but almost linearly proportional to the pressure. In other words, it is far more efficient to deploy 10 200 cu.in. guns than 1 2000 cu.in. gun at the same pressure.
2. To provide the ability to steer the beam predominantly downwards through the mechanism of directivity.
3. To improve reliability. Losing a couple of guns from 30 has a negligible effect on the array performance although oil industry representatives seem to worry far more about this than they should and the drop-out behaviour of an array, (which involves modelling every possible unique combination of dropping out several guns from many, a herculean modelling effort), is closely monitored.
4. To shape the signature pulse so that it is easy to deconvolve its effects in the recorded data, [2].

Of these, the last is generally considered the most important.

Spatially the guns might be distributed in 3-6 sub-arrays spread over an area of perhaps 40m at right angles to the boat direction and 20m parallel to the boat direction. They are typically deployed at depths between 2m. (small arrays often used by high resolution surveys or transition surveys mixing land and marine recorded data) down to 20m or so for deep penetration.

A more detailed description of their properties can be found in [1].

2 THE ACOUSTIC RADIATION FIELD OF AN AIRGUN

2.1 MODELLING AIRGUNS

The theory and modelling of single airgun behaviour was introduced by Ziolkowski in 1970, and later developed through a series of papers by Ziolkowski, Vaage and collaborators, [3], [4]. This work laid down the idea of modelling the pressure waveform by solving the differential equations of motion including heat transfer and bubble motion.

Later it became clear that because each gun is modulated by the pressure field of all the guns in its vicinity, the signature of an array of guns is typically very different from the linear superposition of the gun signatures of each gun discharged in isolation. This led to the concept of a *notional source*, [5], [6]. A notional source is the equivalent source to an airgun in which the interaction or modulation effects have been factored into the behaviour of this non-physical source. The important point is that notional sources can indeed by linearly superposed with suitable delays to model the total radiated field in any direction and still take full account of the pressure-field interaction effect. This opened the door to sophisticated modelling of airgun arrays and effectively replaced the need to measure them each time.

This concept was later extended to energy-field interaction, a much longer scale effect by [7].

As the years went by, it was realised that airguns in very close proximity, (approximately 1m apart), also known as *clustering*, enjoyed special properties. Although the peak to trough pressure of the array was reduced somewhat because the external pressure field effectively throttles individual guns, the strong interaction was observed to depress the oscillatory bubble very significantly leading to a signature pulse much closer to the ideal of a Dirac delta function waveform. This was demonstrated in modelling for the first time by [8].

Since then, there have been incremental improvements in dealing with the very strong pressure-field interaction in modern arrays and extension to higher frequencies by Hatton [9], but to all intents and purposes, airgun modelling is now as good as experimental error in actually measuring the output signature pulse in the presence of real-world factors such as time-varying undulating sea-surface, relative motion with respect to the rising bubble and so on.

2.2 CALIBRATION

Models are of course only as good as their calibration. In the early days, high-quality data recorded in specialist facilities in water deep enough to avoid interference from bottom and side reflections such as Norwegian fjords, were relatively rare. Today the situation is different with most large companies having extensive datasets of such measurements which can be used to calibrate modelling packages such as [10].

2.3 THE SIGNATURE AND AMPLITUDE SPECTRAL RESPONSE

A typical model of a signature is shown in Figure 1. The y-axis of the time-domain plot is calibrated in bar-m. This is the number of bars which would be measured 1m. directly underneath a point source of this behaviour. The amplitude spectrum is calculated with respect to db. relative to 1mPa/Hz at 1m. following the excellent standardising work of [11]. As can be seen, the spectrum has its peak value in the 20-80Hz band which is more or less ideal for exploration seismology and is around 35db down on this at 500Hz.

2.4 THE HIGH FREQUENCY AMPLITUDE SPECTRAL RESPONSE

Until 2003, there was relatively little data available outside military circles for frequencies in the kHz range. In 2003, the Industry Funders Research Council (IFRC) funded an experiment to measure a real seismic array in normal use out to 25kHz.

The amplitude spectrum of this data (which was measured approximately 700m from the array), is shown in Figure 2. As can be seen, the spectral response falls rapidly by around 50db in the first 1000Hz and then tails off a little falling a further 20db in the next 4000 Hz and then bottoms out at around 80db down on its peak value (occurring at about 50Hz).

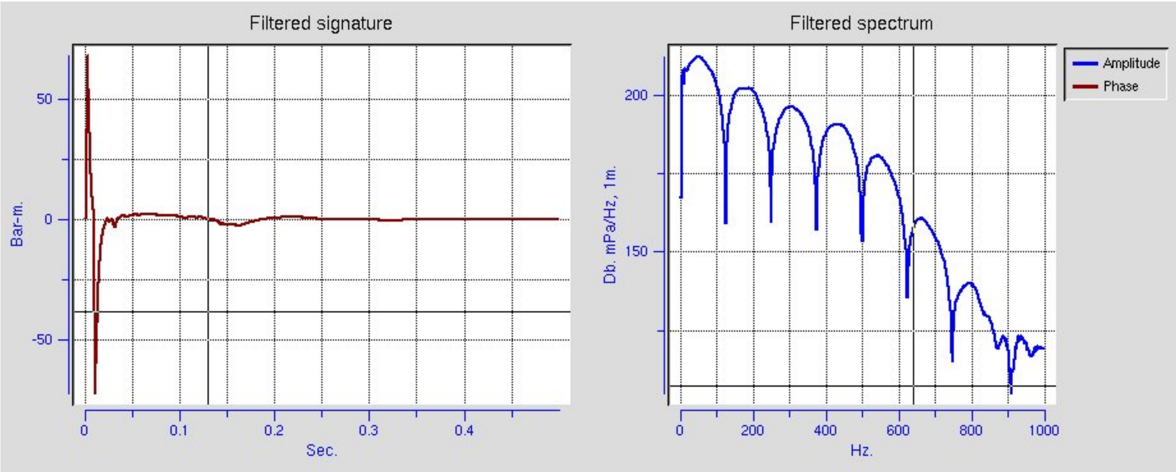

Figure 1: A computer model of a typical array of airguns used in exploration seismology. This array is 3100 cu.in. in total volume and consists of three sub-arrays of 8 guns each. The array has been filtered to a bandwidth of 0-512 Hz. The regular notching in the amplitude spectrum is due to the virtual image of the source in the free surface. It is known as the surface *ghost*.

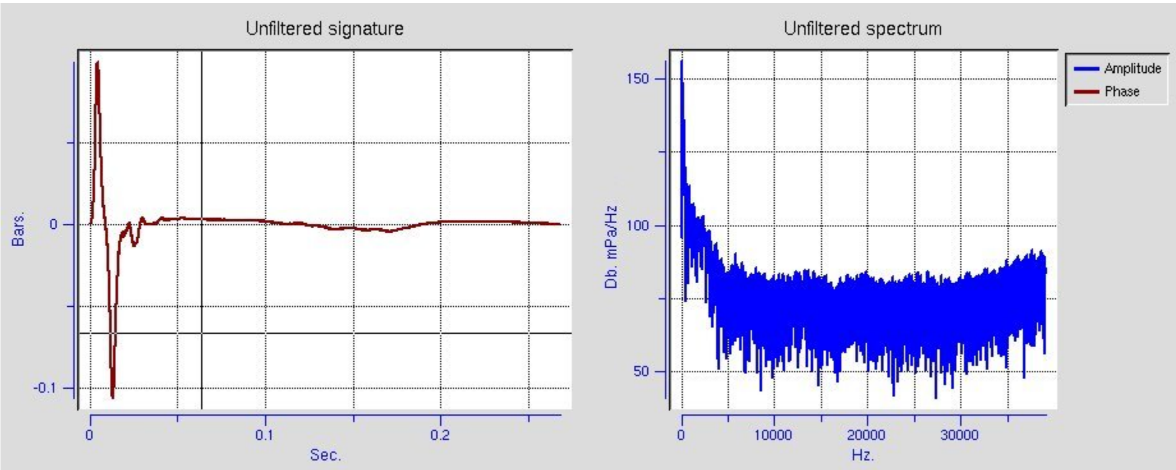

Figure 2: A recorded broad-band signature taken approximately 740m underneath a seismic survey vessel discharging an array of around 3590 cu.in. comprising 31 guns, (data released courtesy of IFRC). Note that the pressure here is measured in bars and the spectra iin db relative to 1mPa.

It is worth noting that in this same experiment, the seismic survey vessel's depth transponder, (which pings at 18kHz) is around 20db *higher* than the airgun array at this frequency.

A model of this array is shown in Figure 3. Given that the model takes no account of propagation effects in a stratified ocean, depth variations in the array, absorption or the known and unpredictable anisotropy at high frequencies in the oscillating bubble, [12], it is gratifyingly close to Figure 2 and suggests that nothing new need be introduced into the physics of modelling airguns to get an excellent estimate of the overall spectral level at high frequencies.

2.5 THE HIGH FREQUENCY ENERGY BUDGET

Given the supporting evidence of the IFRC experiment, it seems appropriate to calculate energy budgets for various bandwidths directly from the models.

There are two ways of calculating the total energy budget of a multi-gun seismic array. By far the most efficient is the near-field method which uses the notional sources as first described by [7].

$$E=\sum_{m=1}^{n}\left[\left(\frac{(4\pi)}{pc}\right)\int_{-\infty}^{\infty} s_m^2(t)\,dt+\left(\frac{(4\pi)}{p}\right)\int_{-\infty}^{\infty} p'_m(t)\left[\int_{-\infty}^{t} s_m(t')\,dt'\right]dt\right]$$

where E is the energy, $s_m(t)$ is the mth notional source and $p'_m(t)$ is the predicted pressure field at source position m due to the other n-1 sources.

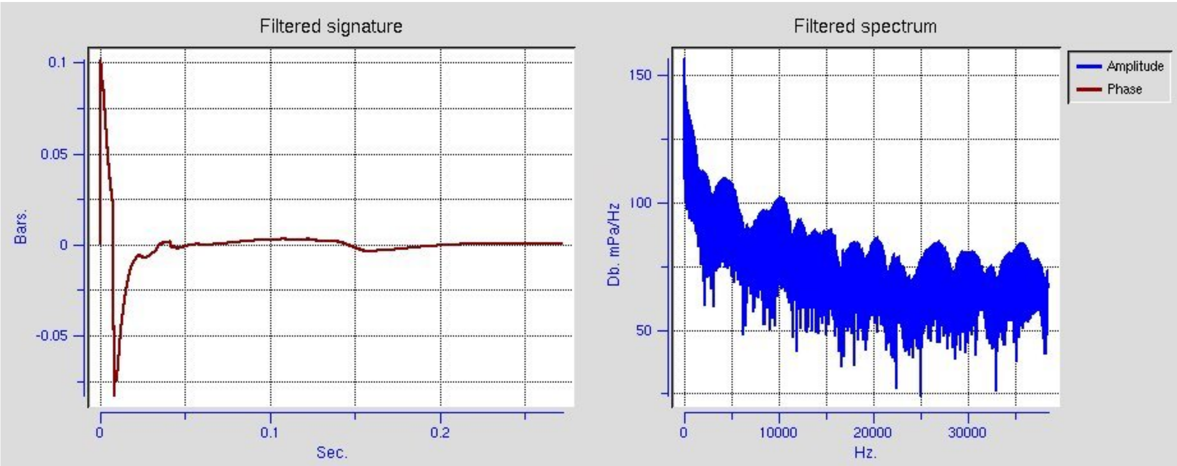

Figure 3: A computer simulation of the IFRC dataset shown in Figure 2.

Using this method, the energy budget of the 3590 cuin array used in the IFRC dataset was modelled in a number of bandwidths and the total energy in Joules measured in each case from its equivalent set of notional sources. The results are shown in Figure 4. For reference, the amount of acoustic energy above 12,500Hz is around 100 Joules representing only around 0.06% of the total acoustic energy budget of around 177,000 Joules. Note that this budget includes all effects attributable to the surface reflection.

For a range of 500m, this represents an average acoustic energy flux of around $6 \cdot 10^{-5}$ Joules per square metre for each array discharge.

3 ACOUSTIC SENSITIVITY OF MARINE ANIMALS

3.1 THE CURRENT STATE OF UNDERSTANDING

It is almost certainly true to say that airgun physics is much better understood than the effects of external human-based acoustic sources on marine animals either in the sense of discomfort caused or interference with echo-location in the case of the odontoceti. One of the seminal references in this area is the work of [13]. Marine species collectively hear over the full range of 5-200,000Hz. An example of audiogram sensitivity is shown in Figure 5.

There remain a number of outstanding problems. Behavioural experiments on animals are fraught with complication, notably, effects can only be inferred. Here, any anticipated effect will be simulated by having a human diving in the vicinity of the IFRC array described in this paper equipped with sensory equipment for frequencies greater than about 15kHz and simply their ears for frequencies below this. It is hoped that this will provide at least a reasonable analogy.

3.1.1 UNITS

The units of pressure measured by marine biologists may be rather different than those measured by exploration seismologists. By far the most sensible measure is the one used by exploration seismologists and introduced above by [11] which is independent of either sampling interval or signature duration and that is the pressure measured in db relative to 1mPa/Hz at 1m. It appears however, [13], that animals may integrate over some bandwidth in which case a unit of db relative to 1mPa at 1m over some spectral window (either 1/3 or full octave are both used) is more appropriate although it is far from clear which. Figure 5 is calibrated in these units although the degree of integration is unknown. A further complicating factor presents itself in that it is believed that fish 'hear' the particle velocity field utilising hairs in the inner ear rather than the pressure field registered by mammals.

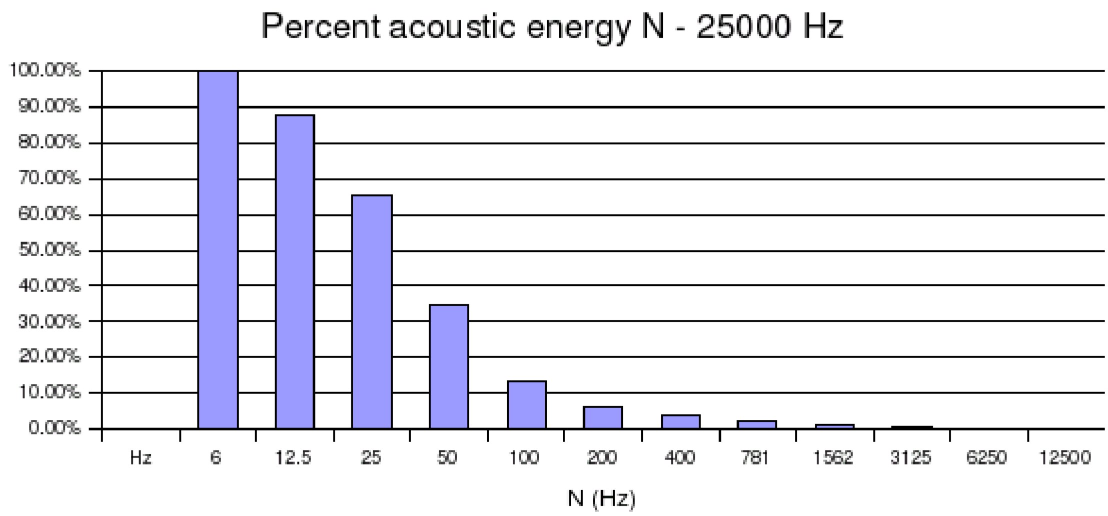

Figure 4: The energy budget as a percentage of the total energy in Joules in each of a number of bandwidths N - 12500 Hz for different values of N. For example 6-12500Hz effectively contains all the energy but the range 3125 -12500 Hz contains much less than 1%.

3.1.2 PAIN

The intensity at which humans find acoustic energy painful is around 9 Joules / m^2, [13] (p. 17). Since human ears are sensitive in the range 20-15,000 Hz approximately, the human ear would hear the vast proportion (more than 99.9%) of the acoustic energy emitted by an airgun array. Now the total acoustic energy budget of the IFRC array is 177,000 Joules, so given the above limit then, it would be expected that a human might experience pain on average anywhere within a range r, where:-

$$\frac{177000}{(2\pi r^2)} \geq 4.5$$

assuming that the energy flux takes place over 0.5 second, the effective duration of an airgun bubble train. This gives an approximate range r = 140m. within which a human would feel pain on average. Directional effects would increase this in some directions at the expense of others, (notably in the vicinity of the surface where the acoustic field is zero due to the presence of the virtual sources caused by the free surface and the human would not hear a thing.

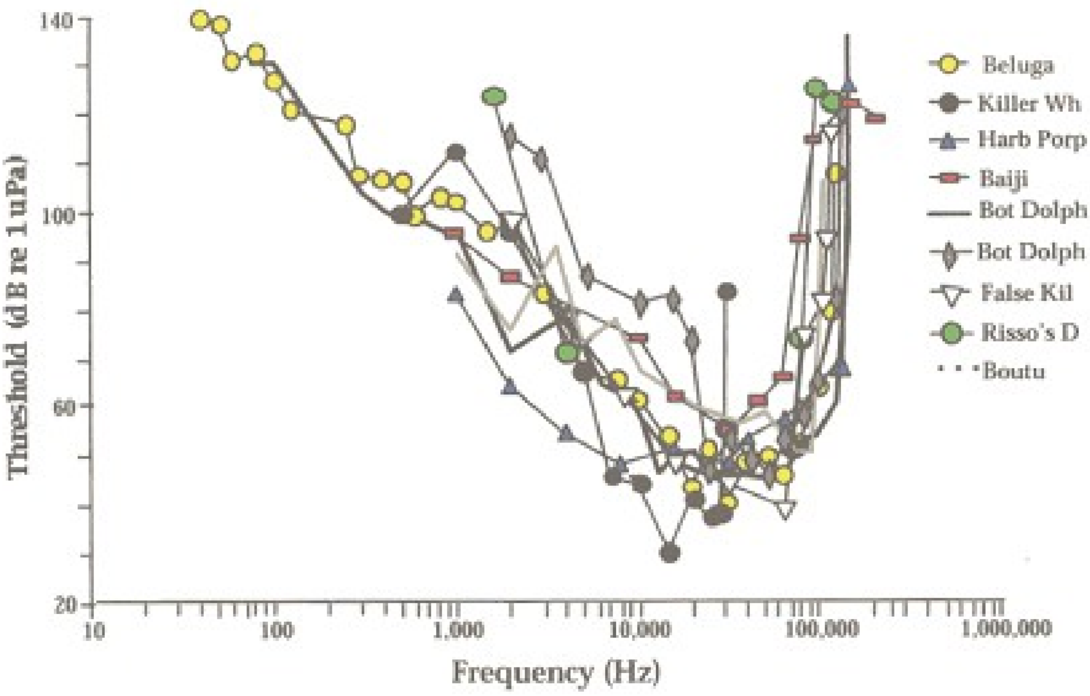

Figure 5: Audiogram data assembled from sources such as [13] for various species.

3.1.3 ECHO-LOCATION

According to the table cited on p. 182 of [13], the typical source level issued by echo-locators from Baiji up to the false Killer Whale is in the range 156-228 db re 1mPa at 1m at frequencies of typical 20kHz upwards to as high as 150kHz. Suppose then the human diver was equipped with an echo-location system with a source strength of 160db at 20kHz. Given that some of the most capable sonar equipment was designed using properties which naturally evolved in the animal world, for example in bats, [14], it is not unreasonable to assume that the equipment would be no better than the animals doing the same job in the environment in which they evolved.

If the data in Figure 2 is referenced back to 1m. 57db has to be added at each frequency. For 20kHz and upwards the amplitude spectral strength of this airgun array is therefore around 155db relative to 1m.. In digital signal processing, it is comparatively simple to extract signal when the signal to noise ratio exceeds 4 to 1, which corresponds to around 12 db. It is reasonable to expect therefore that animals can do the same thing and probably evolved such high source levels to combat natural sea noise or absorption at these frequencies. For the worst case of 156db in the case of the Baiji, an animal would only need another 11db or so to be able to discriminate comfortably. Even given cylindrical spreading, this would occur within 20 or so metres of the source.

4 CONCLUSIONS

The current quality of modelling of marine airgun sources is generally excellent and is within experimental error on the wide range of experimental data now available. At higher frequencies, although there is currently only one dataset out to 25kHz, again agreement with the experimental data with a conventionally calibrated airgun model is excellent in terms of defining the background level at high frequencies.

The effect on marine animals remains difficult to quantify. An analogy of a human diver is presented here suggesting that pain would be felt with a typical array with a range of approximately 140m and that echo-location equipment operating at 20kHz would be effective up to approximately a range of 20m. Until more experiments are forthcoming in the marine biology community it is hard to be more specific than this.

5 REFERENCES

[1] G.E. Parkes and L. Hatton, The Marine Seismic Source, 1st edition, van Reidel, ISBN 90-277-2228-5 (1986).
[2] L. Hatton, M.H. Worthington and J. Makin, Seismic Data Processing: theory and practice, 1st edition, Blackwell, ISBN 0-632-01374-5(1986).
[3] A.M. Ziolkowski., 'A method for calculating the output pressure waveform from an airgun', Geo. J. Royal Ast..Soc. 21 137-161. (1970)
[4] S. Vaage, S. Strandness and T. Utheim, 'Signatures from single airguns', Geophysical Prospecting. 31 87-97. (1984)
[5] A.M. Ziolkowski, G.E. Parkes, L. Hatton and T. Haugland, 'The signature of an airgun array: computation from near-field measurements including interactions', Geophysics. 47 1413-1421 (1982)
[6] G.E. Parkes, A.M. Ziolkowski, L. Hatton and T. Haugland, 'The signature of an airgun array: computation from near-field measurements – practical considerations', Geophysics. 49 105-111 (1984)
[7] R.M. Laws, G.E. Parkes, and L. Hatton, 'Energy-interaction: The long-range interaction of seismic sources', Geophysical Prospecting. 36, 333-348 (1988)
[8] R.M. Laws, L. Hatton and M. Haartsen, 'Computer modelling of clustered airguns', Geophysical Prospecting First Break. 8(9), 331-338 (1990)
[9] L. Hatton, 'Incorporating marine mammal hearing sensitivity into a high-grade airgun modelling package (extended abstract)', PETEX 2004, abstract available at http://www.leshatton.org/PETEX04.html
[10] L. Hatton, 'Gundalf – an airgun array modelling package', http://www.gundalf.com/ (2002-)
[11] J.R. Fricke, J.M. D.H. Davis and Reed "A standard quantitative calibration procedure for marine seismic sources", Geophysics, 50(10), p. 1528-1532 (1985)
[12] L. Hatton, 'Commentary on two airgun videos', http://www.leshatton.org/two_airgun_videos.html, (2007)
[13] W.J. Richardson, C.R. Greene, C.I. Malme and D.H. Thomson, Marine Mammals and Noise, 1st edition, Academic Press, ISBN 0-12-588441-9 (1995)
[14] R. Dawkins, The Blind Watch-Maker, 3rd edition, W.W. Norton, ISBN 0-393-31570-3 (1986)